water

Case Report

Experience from the Implementation and Operation of the Biological Membrane Reactor (MBR) at the Modernized Wastewater Treatment Plant in Wydminy †

Iwona Skoczko *, Pawel Puzowski and Ewa Szatyłowicz

Department of Technology in Environmental Engineering, Faculty of Civil and Environmental Science, Bialystok University of Technology, Wiejska 45A, 15-351 Bialystok, Poland; pawel.puzowski@wp.pl (P.P.); e.szatylowicz@pb.edu.pl (E.S.)

* Correspondence: i.skoczko@pb.edu.pl; Tel.: +48-607-615571

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Abstract: Biological membrane reactors or membrane bioreactors (MBRs) based on pressure separation techniques are placed among the latest and most modern methods of wastewater treatment. Currently, this method is becoming more and more popular and is being implemented in smaller and larger wastewater treatment plants (WWTPs). However, technologists, operators, and managers of small WWTPs often do not understand the MBR technology installed in their sites and need extensive professional and technological information. The aim of this study was to analyze the modernized WWTP in a small town of Wydminy, located in northeastern Poland in the Great Masurian Lakes region, where the traditional secondary settling tank was replaced by an MBR. The effectiveness of wastewater treatment before modernization and after installation of the membrane module was compared. On the basis of the conducted research, it was noted that the operation of the plant after modernization is more cost-intensive. There were additional electricity costs due to ensuring adequate pressure on the membrane. Nevertheless, the obtained results of the removal of contaminants place the plant in Wydminy in the group of the most effective Polish sewage treatment plants, as compared to the results obtained in other facilities. The MBR operation also places high demands on the exploiters, prompting them to observe even the smallest changes. The conducted research is a type of a case study, which could give the readers an understanding of the necessity of traditional WWTP modernization with MBR.

Keywords: biological membrane reactors MBR; wastewater treatment plant; sewage quality

1. Introduction

With the invention of biological membrane reactors or membrane bioreactors (MBRs), wastewater treatment technology climbed to another level. These devices, based on pressure separation techniques, are among the latest and most modern methods of wastewater treatment. The first MBR was installed in 1960 in the United States of America and introduced by DorrOliver, while, a few years later, the next one was introduced in Tokyo Japan. In 1997, the first MBR installation was completed in Europe, as part of the municipal wastewater treatment plant in Porlock, United Kingdom (UK). Currently, the method is becoming more and more popular [1]. There is a rapid development of solutions used in this technology (materials, membrane modules, installation methods). MBR is focused on innovation and introduces more and more improved systems and innovative installation procedures [2]. Taking into account climate change and limited water resources, further intensive development of the MBR technology is expected, changing treated wastewater into a rich source of water [3]. The MBR method allows treating was so effectively that it can transform to a valuable raw resource. The market of membrane producers responds to the growing demand for their products and, every year, they reduce their prices, thus increasing the number of sold devices [4].

The growing interest in membrane bioreactor (MBR) technology has opened up new opportunities for wastewater treatment plant (WWTP) operators. The facilities using membrane modules, which were built in recent years, allow effectively eliminating operational problems in the wastewater treatment process, increasing the effects of removal of pollutants, and minimizing the negative impact of the WWTP on the environment. Technologies based on MBRs can be used for many applications, such as industrial and municipal wastewater treatment, as well as water treatment [5,6]. Today, scientists [6–8] believe that these are the best available methods (BAT—best available technology). The method of membrane installation at the WWTP is influenced by its execution, simplicity of installation, and economic aspects [9]. The technology using MBRs is an improvement and intensification of the activated sludge method. Frechen [10] and Konieczny [9] indicated that the basic difference is most often the replacement of the secondary settling tanks, occurring in the classical activated sludge scheme, with a system of porous (usually micro- or ultrafiltration) filtration membranes placed directly in the aerated activated sludge chamber. The membrane module can also be designed as a separate unit in a separate tank, similar to that installed by Gnirss and Lesjean [11]. According to Konieczny [12], two MBR configurations are used in the wastewater treatment technology. The membrane module can be submerged in the biological chamber and then forms one unit with it. However, as Hackner [13] noted, the membrane and the aeration chamber can also be separate devices. The main difference is that, in the case of compact units, i.e., when the membrane is in a biological reactor, only the wastewater treated as permeate flows out. Active sludge remains in the reactor. In the second case, when the membrane module and the reactor are separate devices, there is a need to foresee the recirculation of concentrated wastewater (retentate), as well as sludge, back to the beginning of the treatment system or to the reactor, as also confirmed by Le Clech and his team [14]. As a rule, the main role of the membrane module is to separate activated sludge from treated wastewater, and the module itself serves as a classic secondary settling tank. Biological membrane reactors or membrane bioreactors (MBRs) have many advantages over traditional activated sludge reactors, the most important of which are very high phase separation efficiency, high quality of treated wastewater and the possibility to remove specific micro pollutants (e.g., pharmaceuticals), smaller reactor volume due to the higher sludge concentration used, and smaller amount of extra sludge produced [7,14–17].

Designed small sewage treatment plants located in northeastern Poland in the 1970s and 1980s were designed especially for villages, small towns, or industrial plants [9,15]. Most of these plants still operate today. However, the local conditions have changed, as well as the number of inhabitants using the sewage system. The capacity of the plant has decreased due to the growing ecological awareness of society and water saving [18]. The internal environmental law of European Union (EU) Member States has been adjusted to the existing directives. This has resulted in stricter legal regulations of the quality of wastewater discharged to the environment, especially to receivers used for recreation in natural and valuable areas. The WWTPs were intensively operated and, at the same time, their modernization was not carried out due to a lack of financial resources, e.g., EU funds. Thus, there was significant wear and tear of the equipment, the effect of the sewage treatment decreased, and the capacity of the plant changed. All of these factors influenced the necessity to rebuild many small Polish WWTPs in terms of changing the hydraulic load and treatment technology. In the most recent literature on the subject, there can be found a lot of data concerning the efficiency of wastewater treatment in membrane reactors of different capacity [19–21]. However, there is no information concerning the operation of Polish treatment plants with membrane reactors [20,22]. Technologists, operators, and managers of small wastewater treatment plants need extensive professional and technological information. The issues should be considered separately if the facility is located in a tourist resort, which is related to the increased inflow of sewage in the summer season. In view of the above, this paper analyzes the modernized operation of the sewage treatment plant in Wydminy, located in northeastern Poland in the Great Masurian Lakes region, where the traditional secondary settling tank was replaced by an MBR. The effectiveness of wastewater treatment before modernization and after installation of the membrane module was compared.

2. Material and Methods

In 2019, the process of reconstruction of the existing biological WWTP was started in Wydminy, located in northeastern Poland in the Great Masurian Lakes region. The works were carried out within the framework of a project co-financed by the Regional Operational Program of the Warmińsko-Mazurskie Voivodeship for the years 2014–2020, Priority 5 "Natural environment and rational use of resources", Activity 5.2 "Water and sewage management". The project was called "Modernization and extension of the sewage treatment plant in Wydminy".

2.1. Technological System before Modernization

The analyzed WWTP was originally designed for the treatment of wastewater with a daily average capacity of 767 m^3/day, maximum daily capacity of 1222 m^3/day, maximum hourly capacity of 64 m^3/h, and maximum annual capacity of 464 725 m^3/year, according to Decision No. WŚ.6341.6.2.2016 from 14 March 2016. The actual amount of sewage discharged from the treatment plant in Wydminy 83,003 m^3 in the year 2015, giving a daily average capacity of Qav = 227 m^3/day (Table 1).

Table 1. Quantity of sewage discharged to the sewage treatment plant in Wydminy.

Year	2013	2014	2015
Quantity (m^3/year)	92,280	84,824	83,003

Source: Own elaboration.

Raw sewage flows into the plant from the Wydminy commune including neighboring towns Wydminy, Mazuchówka, and Gawliki Wielkie. The composition of raw sewage is given in Table 2. The main difference between the two systems is that the process of separating activated sludge from sewage was carried out in radial secondary settling tanks. The settling tanks were equipped with a sludge scraper together with a system for scraping and discharging floating parts. Currently, it is replaced by an MBR.

Table 2. Contamination indicators for raw sewage flowing into the treatment plant in Wydminy before and after modernization.

Average Concentration of Pollution Parameter	Average Load of Pollution Parameter before Modernization	Average Load of Pollution Parameter after Modernization
Biological Oxygen Demand BOD 1200 mg O_2/L	BOD 920.4 kg O_2/day	BOD 360.0 kg O_2/day
Chemical Oxygen Demand COD 2520 mg O_2/L	COD 1932.8 kg O_2/day	COD 756.0 kg O_2/day
Total suspended solids 1460 mg/L	Total suspended solids 1120 kg/day	Total suspended solids 438.0 kg/day
Total nitrogen 150 mg N/L	Total nitrogen 115 kg N/day	Total nitrogen 45.0 kg N/day
Total phosphorus 25 mg P/L	Total phosphorus 19.2 kg P/day	Total phosphorus 7.5 kg P/day

Source: Own elaboration.

Biologically treated wastewater from the WWTP in Wydminy is discharged to a receiver, which is a closed Ø 300 mm channel with a length of 160 m, founded at a depth of about 2 m and ended with a W-1 type concrete outlet to the Wydminski Canal. The 3 km long canal leads to the Gawlik river and is connected with the lake.

2.2. Technological System after Modernization of the Plant

According to the data from the Polish National Urban Wastewater Treatment Program, the town of Wydminy belongs to the agglomeration classified with the symbol PLWM060 and population equivalent (PE) 3810 [23]. However, in reality, the treatment plant should be classified as PLWM0600 and PE 2896. Therefore, the composition of the discharged wastewater should correspond to the parameters specified in the Regulation of the Minister of Environment of 16 December 2014 (Journal of Laws 2014, item 1800) [24], as given in Table 3.

Table 3. Acceptable values of pollution of waters entering the receiver. PE, population equivalent.

No	Parameter	Unit	Maximum Permissible Limit Values of Pollutants Indicators for Wastewater Discharged into the Water from Sewage Treatment Plants for the Agglomeration
			For the Agglomeration PE 2000–9999
1	BOD	mg O_2/L	25
2	COD	mg O_2/L	125
3	Total suspended solids	mg/L	35
4	Total nitrogen	mg N/L	15
5	Total phosphorus	mg P/L	2

Source: Own elaboration.

According to current data concerning a population equivalent of about 2668 and producing about 220 m^3/day of sewage, there was a need to modernize the analyzed treatment plant. Therefore, a change in the quantitative balance of sewage flowing into the plant was considered. It was assumed that Qdav = 300 m^3/day, Qhav 12.3 m^3/h, Qmax year = 120,000 m^3/year, and Qhmax = 50 m^3/h. The reduction of the hydraulic load had a significant impact on the change in raw sewage pollution loads flowing into the treatment plant (Table 2).

As part of the task “Modernization and extension of the sewage treatment plant in Wydminy”, new objects supporting proper operation of the analyzed plant were built, such as shelters for storing dehydrated sludge, the MBR service building, the shelter’s sewage canal, the air pipeline to the MBR, and the internal supply line for all the equipment of the plant. The modernization of the treatment technology was carried out by replacing the equipment in the drainage point (place where the vacuum trucks deliver wastewater to the treatment plant) and the equalizing tank for the delivered wastewater, the grating building, the centrifugal sandbox, the biological block including the chambers of dephosphatation, denitrification, and nitrification, the pumping station, and the mechanical sludge dewatering station. In addition, the chambers of the equalizing tank, the biological block, the coagulant tank tray, and the grating building, as well as the mechanical sludge dewatering station building, were renovated. The equipment used for sewage treatment before and after modernization is given in Table 4.

The goal of the project and research was development and modernization of the WWTP. It was assumed that the process should be carried out with possible usage of the existing infrastructure, while the process of previous active sludge sedimentation in the secondary settling tanks would be replaced by a membrane bioreactor (with equipment necessary for its operation). Therefore, the most important element of the modernization was the adaptation of the secondary settling tank for the needs of the MBR and the construction of the infrastructure supporting its operation, including the arrangement of a compressed air installation led from the new MBR service building to the reactor itself.

As part of the project, one of the secondary settlers was adapted to the MBR chamber. The adaptation scheme is shown in Figure 1. Due to the existing height system of the plant, it was assumed that one of the secondary settlers would be used for the needs of the MBR, while the other could be liquidated. Plate and pipe membranes were used, which are directly immersed in the activated sludge. The permeate (treated wastewater) flows by gravity from the membrane to the receiver. The module is additionally equipped with an aeration system at the bottom which causes the air stream to flow to the top and washes the entire membrane surface [25]. For proper system operation, there are required turbocompressors with a capacity of 123–426 m^3/h, pressure of 500 mbar, and power demand of 3.0/8.7 kW.

Table 4. Comparison of wastewater treatment equipment in Wydminy before and after modernization. MBR, membrane bioreactor.

Technological System before Modernization	Technological System after Modernization
Mechanical point for delivered wastewater (by septic trucks) with equalizing tank,	mechanical point for delivered wastewater (by septic trucks) with equalizing tank,
step screen,	step screen,
centrifugal sand–grit separator,	centrifugal sand–grit separator,
dephosphatation chamber,	dephosphatation chamber,
denitrification chamber,	denitrification chamber,
nitrification chamber,	nitrification chamber,
system for simultaneous coagulation,	system for simultaneous coagulation,
radial secondary settling tank	MBR,
stuttering and oversized pumping station for recirculating and excessive sludge,	new pumping station for recirculating and excessive sludge,
mechanical thickener,	gravitational thickener,
mechanical station for sludge dewatering with low efficiency	mechanical station for sludge dewatering and sanitizing.

Source: Own elaboration.

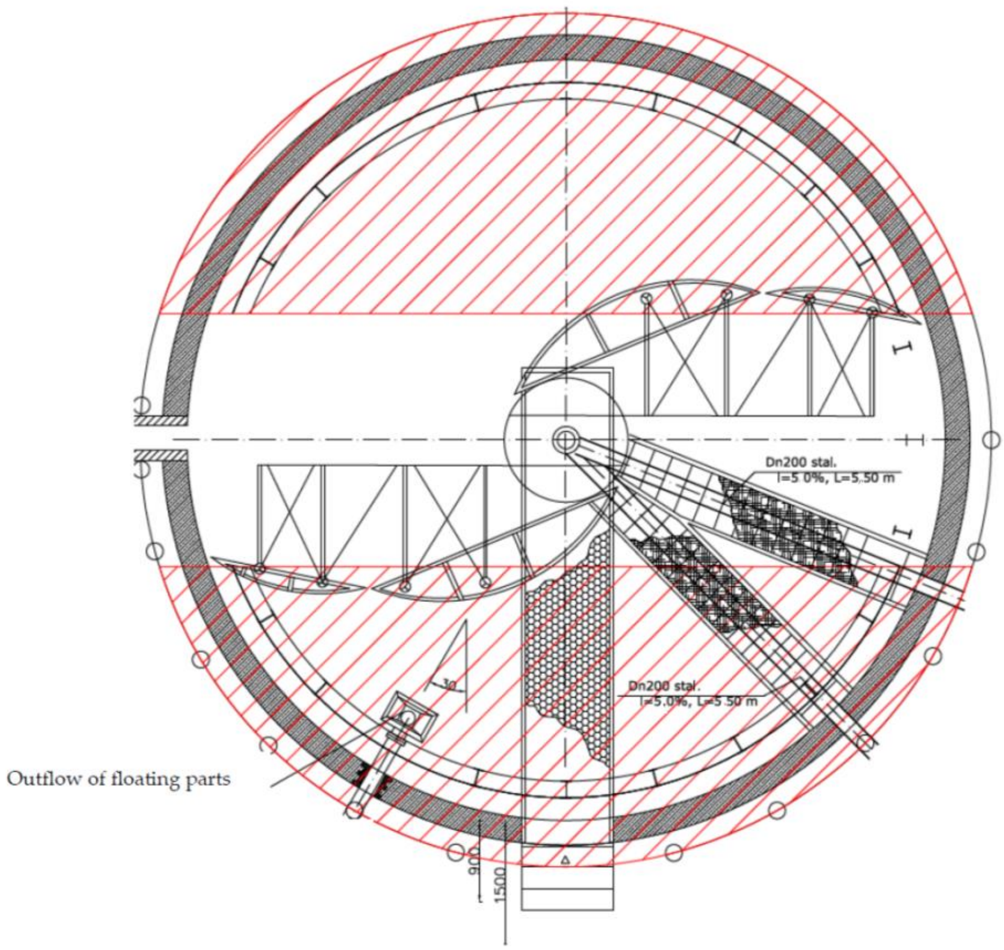

Figure 1. Scheme of adaptation of the existing secondary settling tank to the MBR chamber. Source: Architectural and construction project of the wastewater treatment plant (WWTP) in Wydminy by BACT-sp. Z o.o. [26].

Membranes used in the analyzed MBR in Wydminy have the following parameters:

- flat-surface membrane module;
- recommended cross membrane pressure—10–40 mbar;
- area of installed membranes—1232 m^2;
- number of installed modules—4;
- air quantity for rinsing the modules—0.10–0.15 $Nm^3/m^2/h$;
- maximum temperature—50 °C;
- pH range—1–11;
- membrane material— Polyvinylidene Fluoride (PVDF);
- Pumpless permeate discharge (by gravity).

2.3. Analytical Methods

The research was carried out in the conditions of an operating wastewater treatment plant with a real hydraulic and pollution load, which constituted about 50% of the maximum projected load (before modernization). Technological research was carried out in the years 2016–2020. The quantity of incoming wastewater was measured, and the quality of incoming wastewater and treated wastewater (discharged from the MBR biological reactor) was analyzed for indicators required by the Polish Minister of Environment (Journal of Laws 2014 item 1800) [24], i.e., organic pollutants: Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD-Cr), total suspended solids, biogenic compounds (total nitrogen and total phosphorus), heavy metals (arsenic, chromium, zinc, cadmium, copper, nickel, lead, and mercury), silver, and vanadium. Methods of analysis are presented in the Table 5.

Table 5. Norms and methods used for analytical pollution indicators.

No	Nazwa Wskaźnika	Unit	Analytical Methodology	Norm
1	BOD_5	mg O_2/L	Spectrophotometric method with allylthiourea addition	PN-EN ISO 5815-1:2019-12
2	COD	mg O_2/L	Spectrophotometric method	PN-ISO 15705-2005
3	Total suspended solids	mg/L	method with filtration through glass-fiber filters	PN-EN 872:2002
4	Total nitrogen	mg N/L	Specific method	PB-102, 2nd ed.14 August 2012
5	Total phosphorus	mg P/L	Determination of selected elements by inductively coupled plasma optical emission spectrometry	PN-EN 11885-2009
6	Heavy metals (arsenic, chromium, zinc, cadmium, copper, nickel, lead, and mercury), silver, and vanadium	mg/L	Determination of selected elements by inductively coupled plasma optical emission spectrometry	PN-EN 11885-2009

Source: Own elaboration.

3. Results and Discussion

On the basis of the data presented in Section 2, it can be concluded that the treatment plant in Wydminy was significantly redesigned and the activated sludge system was underloaded. This resulted in insufficient effectiveness of wastewater treatment. The extended time of sewage and sludge storage in the particular chambers led to the release of significant amounts of floating parts, which were not retained in the settling tanks and flowed to the receiver together with the treated sewage. Studies on the quality of treated wastewater conducted before and after modernization proved the need for modernization and showed to what extent the change in technology affected the operation of the plant. The results obtained are presented in Tables 6 and 7.

The quality of treated wastewater leaving the analyzed treatment plant in Wydminy depends on the effectiveness of activated sludge and the conditions in the MBR, which was also confirmed by Judd [27]. Moreover, Le-Clech [28] noted that the wastewater treatment process is affected by the operation continuity of the plant and the efficiency of all used equipment. As part of the modernization project in Wydminy, changes were made to the first stage of treatment (mechanical treatment), whereby the MBR was installed and the thickening system in sludge management was replaced. The automation of the facility for delivered wastewater prevented the discharge of highly concentrated wastewater transported by septic trucks. It made it possible to gradually supply the wastewater to the system, which is systematically diluted with municipal wastewater. Thanks to this process, the active sludge chamber is not periodically affected by a larger load of pollutants, which is responsible for the irregular load of both the chamber volume and the sludge mass. The modernization allowed improving the operation of all systems used in the plant. The sewage flowing into the sewage system and delivered by the septic trucks is currently subjected to screening with a 3 mm step screen. The released screenings are stored, as before, in waste bins and taken out of the plant. The process of sand removal takes place in a sand and grit tank with a whirling flow of wastewater. The separated sand is removed every day by a pump joined to the sand separator. The generated leachate is directed back to the beginning of the treatment system. Mechanically treated wastewater, as in many treatment plants described in the literature [21], is subjected to biological treatment under anaerobic conditions.

Table 6. Detailed analysis of treated wastewater flowing out of the treatment plant in Wydminy after modernization.

Parameter	Unit	I 2019	IV 2019	VI 2019	IX 2019	II 2020	V 2020	IX 2020
pH	-	-	-	7.2	-			7.5
BOD_5	mg O_2/L	5	3	<3	<3	<3	<3	<3
COD	mg O_2/L	78	58	46	35	41	35	44
Total nitrogen	mg N/L	12	4.8	9.3	4.9	10.4	6.36	13.8
Total phosphorus	mg P/L	<0.5	<0.5	0.672	0.605	0.213	0.233	1.73
Total suspended solids	mg/L	18	20	4.2	<2	<2	<2	<2
Volatile phenols	mg/L	-	-	-	<0.010	-	-	<0.010
Copper	mg/L	-	-	-	<0.019	-	-	<0.19
Zink	mg/L	-	-	-	0.051	-	-	0.034
Cadmium	mg/L	-	-	-	<0.0006	-	-	<0.0006
Lead	mg/L	-	-	-	<0.006	-	-	<0.006
Mercury	mg/L	-	-	-	<0.00001	-	-	0.00005
Chromium	mg/L	-	-	-	0.019	-	-	<0.013
Arsenic	mg/L	-	-	-	<0.007	-	-	<0.007
Nickel	mg/L	-	-	-	0.003	-	-	0.003
Silver	mg/L	-	-	-	<0.07	-	-	<0.07
Vanadium	mg/L	-	-	-	<0.008	-	-	<0.008

Source: Own elaboration.

Table 7. Comparison of the values of raw and treated wastewater pollution indicators and treatment efficiency in 2017–2020.

Parameter	Unit	2017				2018				2019				2020			
		Raw Sewage	**Treated Sewage**	**Limit**	**Effect (%)**	**Raw Sewage**	**Treated Sewage**	**Limit**	**Effect (%)**	**Raw Sewage**	**Treated Sewage**	**Limit**	**Effect (%)**	**Raw Sewage**	**Treated Sewage**	**Limit**	**Effect (%)**
BOD_5	mg O_2/L	1360	18.64	25	98.71	880	22.5	25	97.49	530	3.5	25	99.34	300	3	25	99.00
COD	mg O_2/L	7934	124.92	125	98.31	9628	122.33	125	98.75	3460	54.25	125	98.43	1640	40	125	97.56
Total suspended solids	mg/L	>4000	41	35	89.57	>4000	40.55	35	89.98	>2300	11.05	35	99.52	340	2	35	99.41
Total nitrogen	mg N/L	540	14.55	15	97.23	370	13.23	15	97.51	265	7.75	15	98.86	280	10.22	15	96.42
Total phosphorus	mg P/L	41.8	1.98	2	95.65	>50	1.66	2	96.68	>50	0.57	2	98.68	>50	1.73	2	96.56

Source: Own elaboration.

The first object at the analyzed WWTP is an anaerobic dephosphatation chamber equipped with a submersible mixer. To this chamber, the wastewater from the nitrification chamber is recirculated. From the dephosphatation chamber, the mixture of sewage and activated sludge flows into the denitrification chamber. The content of the chamber is mixed with a submersible mixer, and its task is to reduce nitrates. The internal recirculation of sewage from the nitrification chamber is conducted to the denitrification chamber. The nitrification process takes place in the nitrification chamber where the content is mixed and aerated by compressed air, supplied by membrane diffusers. Sludge from the MBR is recirculated into the denitrification chamber. This solution was supported by the fact that the sludge recirculated from the MBR has a high oxygen concentration. As reported by Melin and his group [17] and Liu and his team [16], such a high content would have a negative impact on the operating conditions of the anaerobic chamber. According to their assumptions, it was decided that internal recirculation would be carried out from the nitrification chamber to the anaerobic dephosphatation and denitrification chamber. Before the modernization of the treatment plant, the BOD and COD values reached the upper limit, with a risk of the treatment plant facing sanctions. BOD oscillated around 25 mg O_2/L, while COD was close to 125 mg O_2/L. The total suspended solids in the treated wastewater exceeded the permissible value of 35 mg/L. The content of total nitrogen and total phosphorus, similarly to organic compounds, was close to its limits, i.e., 15 mg N/L and 2 mg P/L. In order to ensure more effective phosphorus reduction before modernization in the effluent, a coagulant with the commercial name PIX was dosed to the final part of the nitrification chamber. Next, the sewage treatment process is carried out in the MBR. The use of the membrane module first of all improved the efficiency of retaining suspended solids from the treatment plant. Their amount decreased from more than 40 mg/L to an average of 11 mg/L, even reaching below 2 mg/L in 2020. Thanks to modernization the effect of using a membrane as a biomass separator, there was partial disinfection of the treated wastewater. The effect of wastewater disinfection increased by keeping most bacteria, protozoa, parasites, and some viruses on the membrane. Researchers of the subject [7,12,14] also emphasized the high efficiency of microbial retention on MBR membranes. Moreover, a layer of activated sludge in the form of a thin biological film accumulates on the membrane surface over time. This allows for the intensification of the purification process and increased efficiency of removal of mainly organic pollutants (COD, BOD, and some biogenic salts). The advantage of using membrane modules is also its retention of organic multimolecular and macromolecular compounds. Wastewater has the possibility to stay in the reactor for a longer time; thus, activated sludge organisms can lead to the degradation of more pollutants. This allows the removal of micropollutants that are difficult to biodegrade, such as pesticides, hormonal substances, and pharmaceuticals. This is due to the fact that a longer sludge age favors the development of specific slowly multiplying bacteria capable of removing these compounds [14,15]. Unfortunately, the biological film on the membrane also has its disadvantage, such as higher pressure demand and lower flow of the wastewater. As mentioned earlier, treated wastewater is finally discharged to the lake, which is used for recreational purposes, including water baths, in the summer season. Wydminy town is a tourist resort, which is recognized by a significant difference in the volume of produced wastewater in the summer and off-season. Hackner [13] noted that the MBR is very flexible in its operation with variable sewage inflows. It allows achieving a stable quality of treated wastewater even in the case of short-term technological disturbances, such as heavy rain or sludge disturbances [12].

In the framework of our own research, it was found that, initially, just after the installation of the MBR, when the unit had no operational continuity, the quality of the permeate was worse. The researchers of the subject gave various explanations for this phenomenon. The Kudlek team [7] confirmed this thesis, while Frechen [10] noticed a clear improvement in cleaning efficiency from the beginning of the MBR. In the analyzed plant operation, in the first months after modernization, the BOD content was 5 mg O_2/L, and the COD content is 78 mg O_2/L. The content of total suspended solids was close to 20 mg/L, that of total nitrogen was 12 mg N/L, and that of total phosphorus was approximately 1 mg P/L. Before modernization, PIX was dosed into the active sludge chamber to improve phosphorus precipitation. Its dosing was considered when the phosphorus concentration in raw sewage was higher.

Currently, PIX is not used as it is not recommended for membranes. Manufacturers allow the use of coagulant based on aluminum, but this preparation is not used in the analyzed treatment plant. After the implementation of the continuous operation of the plant, the quality of the treated wastewater significantly improved. Currently, the obtained results fully meet the permissible values, and the treated wastewater can be discharged to a receiver with high-quality requirements and offering the tourists safe use of its waters. After 9 months of operation of the modernized plant, the BOD content is less than 3 mg O_2/L and the COD content is 35 mg O_2/L. The content of total suspended solids dropped below 2 mg/L, that of total nitrogen dropped below 5 mgN/L, and that of total phosphorus dropped below 0.5 mgP/L.

The new MBR uses Alfa Laval MBR membranes. According to Kozjek and Rosenbom [29], such membranes provide trouble-free wastewater treatment at low operating costs. They are based on patented LowResis technology [26], which ensures low transmembrane pressure during operation. This significantly reduces cleaning and conservation work, as fouling of the membranes is mainly caused by surface contamination, which is easily removed, and clogging of membrane pores is reduced [30]. The used key technology is a microfiltration membrane design which combines high permeability with MBR construction and reduces pressure loss at all stages of permeate production [26]. In the used model, this technology has been improved in order to further reduce the transmembrane pressure. The installed membranes have open sides, which allows the permeate to flow freely into the tank. This leads to a more even pressure distribution on the membrane, which increases efficiency and reduces the need for cleaning. The membranes used combine low cleaning and maintenance requirements with low energy consumption and excellent leachate quality. As noted by Ratkovich and Bentzen [31] and Patsios et al. [32], similar membranes are used worldwide in wastewater treatment plants using MBRs to treat wastewater from various processes, such as municipal wastewater treatment plants, food production plants (including wine, brewing, dairy, beverage, starch, and snacks), pharmacies, chemical industries, petrochemical processing, animal slaughterhouses, and MBR installations in municipal and industrial wastewater treatment plants.

The MBR installed in the analyzed Wydminy WWTP adopts the filter principle. The mixture of sewage and activated sludge flows upward between the membrane elements, while permeate passes through the membrane plate. In order to ensure proper circulation of the sludge and sewage mixture, air bubbles are used to force a cross-flow. This type of flow also affects the cleaning of the membrane surface, as Le Clech [14] confirmed. Regardless of the configuration, the air is injected through an aeration system located at the bottom of the reactor chamber. Chang and his team [33] also reported that the design of the membrane ensures the removal of the permeate from the entire membrane surface. The leachate outlet is located in each corner on top of the module [26]. According to Yang et al. [1], this means that the pressure loss on the clean membrane is close to zero, and, according to Kudlek and Dudziak [2], there are no blind spots on the membrane itself. At the Wydminy plant, it has been noticed that, with a longer operating time, the MBR is covered with a thin biological film, which makes it difficult for the sewage to pass through and be treated effectively. Solid and fibrous parts are the problem, not caught by the screen at the beginning of the treatment line. They are transferred to biological treatment and then to the MBR, accumulating on the membrane. The experience of the Konieczny team [7] proved, however, that regular cleaning of the membrane must be ensured in order not to decrease pressure and capacity. At the Wydminy WWT plant, it was decided to clean the membranes using two methods. The first is to inject air between the sheets of the membranes. The second is to use chemical backwash once every 3 months. The signal indicating an increase in pressure and the need to activate membrane washing comes from transmembrane pressure sensors. Cleaning includes the following sequences: release, refill, and CIP (cleaning in place). Sodium hypochlorite is used for membrane cleaning in the Wydminy plant. Judd et al. [5] highlighted that the changes in the system's operating parameters (permeate filtration pressure, permeate flow) should be observed after backwashing. Optimal adaptation of the appropriate frequency of membrane cleaning allows saving air and chemical cleaning agents, as well as not increasing electricity consumption [34,35].

4. Summary and Conclusions

The modernization of the sewage treatment plant in Wydminy and the application of the MBR allowed obtaining a high, constant quality of treated sewage in comparison with the sewage discharged from the previous technological system with separation in the secondary radial settling tank (Figure 2).

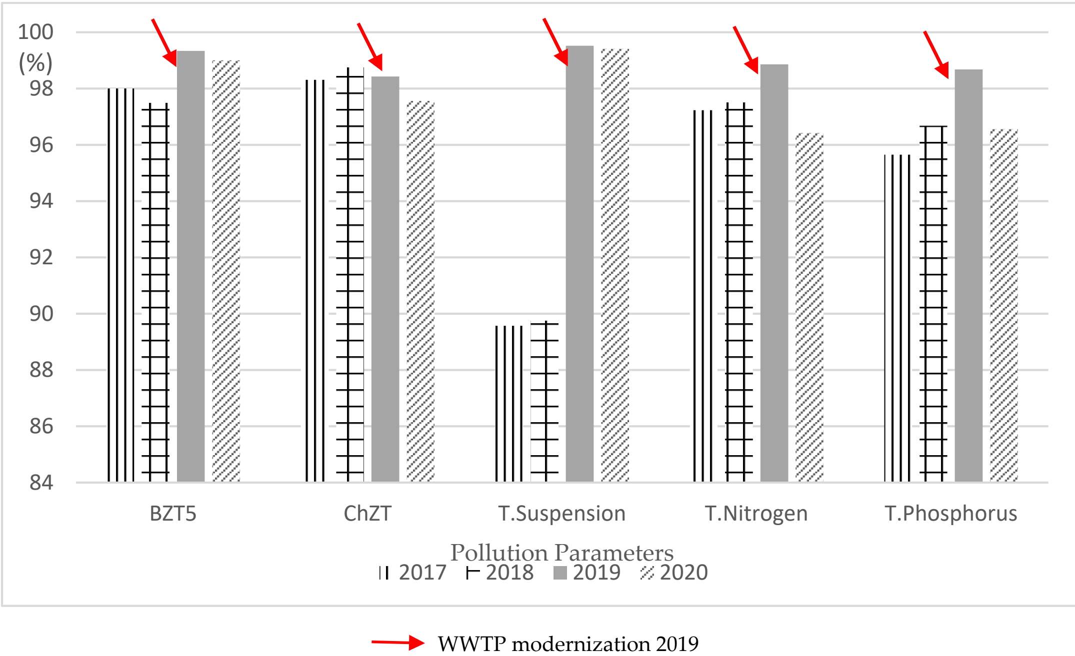

Figure 2. Efficiency of the sewage treatment plant operation in individual years of operation, with specification of chemical parameters. Source: Own elaboration.

Among many positive effects of modernization, very high elimination of suspended solids in the outflow was noted, as well as a lack of problems with the sludge or sludge blanket in the settling tank and, consequently, in the sewage receiver. Previously, a significant number of floating parts migrated to the sewer that discharged treated sewage and to the Wydminski Canal, where treated sewage was a large part of its flow. Thanks to the development of the plant and the use of the latest technologies and materials, there appeared a possibility of increasing the efficiency of the MBR plant in the case of including new areas of the municipality into the catchment area of the plant. On the basis of the analysis of the quality of treated wastewater, high efficiency of treatment was found in the examined plant with a biological membrane reactor. Operators and the laboratory team noticed that the treated wastewater was clear, colorless, and odorless in comparison to the treated wastewater before modernization. In all analyzed samples for indicators describing organic matter (BOD, COD, and total suspended solids), the concentrations of pollutants in the wastewater transferred to the receiver were much lower than the acceptable values according to the current water permit and the Regulation of the Minister of Environment (Journal of Laws of 2014, item 1800). The efficiency of BOD removal in the treatment plant, shown in Figure 2, was over 99.0%, while it was almost 99.0% for COD. The efficiency of total suspended solid removal increased the most, reaching over 99.5%. The average removal degree of biogenic compounds also increased and exceeded 98%.

There also appeared operational problems. It was noted that pollutants from raw sewage pass through the screens and are deposited on the membranes, causing fouling and a significant reduction in flow capacity. There was noted a decrease in wastewater treatment capacity from the originally designed 12.3 m^3/h to 7 m^3/h. The condition for proper MBR operation is effective mechanical treatment, enabling membrane protection. Regular cleaning undoes the reversible fouling of the membrane surface. Managers of the WWTP took the decision to use chemicals as rarely as possible because of biological treatment media. Excessive active sludge goes back to the biological chamber (to equalize the concentration of active sludge in the tank) and to the fermentation chamber. Cleaning chemicals in a form of sodium hypochlorite (NaClO) may cause problems with sewage biodegradation. The reaction byproducts are sodium chloride (salt, NaCl) and water (H_2O), which are transported to wastewater treated in the MBR and going back with the sludge to the biological reactor. The NaCl increase in the solution can lead to dephosphatation and denitrification chambers slowing down biodegradation processes. Active sludge is sensitive to higher salinity, which sometimes may lead to a general decrease in treatment efficiency, form changes (especially of ammonia to nitrate), and phosphate removal. That is why reversible fouling was removed by mechanical treatment of the membrane. Intensive back flushing with treated wastewater was used. When, for the cleaning requirements, backwash was not enough, air injection between the sheets of the membranes was taken into consideration. Irreversible fouling was also noted on the membrane surface. Then, sodium hypochlorite (NaClO) was adapted for retreatment. Chemical cleaning was realized every 3–4 months. Nevertheless, it did not fully solve the fouling problem. On the membrane, surface permanent deposits remained, such as gout, limescale, iron, and silica deposits hard to dissolve. It turned out that the operation of the plant after modernization became more cost-intensive than before. Additional costs of energy have arisen due to ensuring appropriate pressure for the sewage passing through the membrane. Additional external repair and maintenance services necessary for regular MBR cleaning should also be considered, including membrane module replacement. During the study, such a process was run only once when repeated chemical cleaning did not achieve the expected results. Nevertheless, the obtained results in terms of the removal of contaminants, presented by the analyzed pollution indicators, place the wastewater treatment plant in Wydminy in the group of the most effective Polish treatment plants in comparison with the results obtained in other facilities. However, they meet the high expectations of the explorers, prompting them to observe even the smallest changes. The conducted research is a type of a case study, which could give the readers an understanding of the necessity of traditional WWTP modernization with MBR. The old settling tank before modernization and the MBR after modernization are shown in Figure S1 (Supplementary Materials).

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/12/12/3410/s1: Figure S1. Reconstruction of old settling tank (a) to MBR reactor (b).

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